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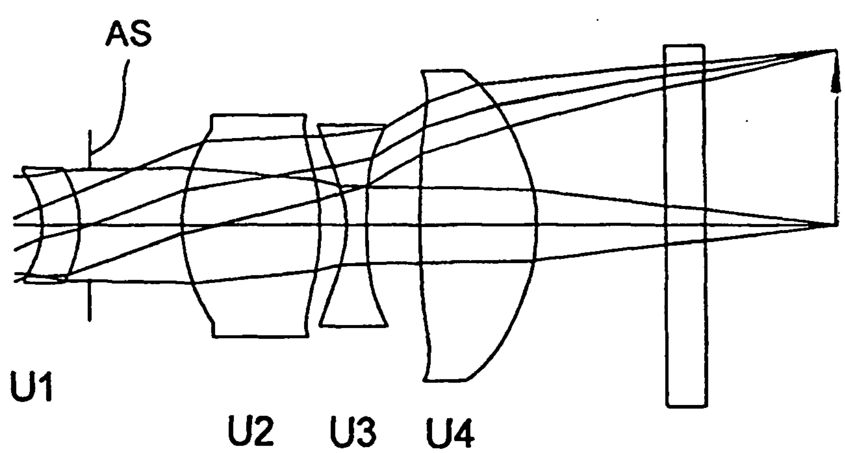
(54) Title: INVERSE TRIPLET LENS ASSEMBLIES

(57) Abstract



Objective lenses employing three lens units (U1, U2, U3) having a negative (or weak positive), positive, negative configuration are disclosed. The lenses have a total field coverage of at least 50 degrees with a relative aperture of less than f/5. They employ small lens elements having aspherical surfaces and are designed for mass production, particularly using plastic optical materials. The designs do not exist in an all spherical form because the aberrations, particularly distortion, cannot be sufficiently corrected, but by using a sufficient number of aspherical surfaces, not only can the aberrations be corrected to a higher degree than a conventional asphereized triplet design, but the sensitivity to manufacturing deviations can be minimized. Optionally, the lenses can include a fourth lens unit (U4) which provides an extended exit pupil which is desirable when the lens is used with a digital light sensor.

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INVERSE TRIPLET LENS ASSEMBLIES

FIELD OF THE INVENTION

This invention relates to objective lenses that contain aspherical surfaces and are designed to be manufactured in high volumes.

More particularly, the invention relates to an inverse triplet objective lens which:

(1) has a negative (or weak positive), positive, negative configuration;

(2) uses aspherical surfaces to correct primary aberrations; and

(3) uses aspherical surfaces to reduce manufacturing sensitivities by reducing the amount of aberration correction contribution by an individual lens element.

In certain embodiments, the negative (or weak positive), positive, negative configuration is followed by a positive lens unit which serves to provide the lens with an extended exit pupil.

BACKGROUND OF THE INVENTION

It is well know that the classical triplet (see Figure 6A and Table 6) can be corrected for all of the primary aberrations, but because there is a residual secondary astigmatism that is not correctable, the performance is limited by astigmatism. If the specifications for the lens are "pushed" too far, the astigmatism is so severe that the depth of focus becomes very shallow (see Figure 6B), and the lens becomes very difficult to manufacture simply because any manufacturing variations will further reduce this already shallow depth.

A further disadvantage of the triplet design is that the spherical aberration and astigmatism correction are both achieved because the

negative element introduces just the "right" amount of aberration of the opposite sign to cancel the effects of the two positive elements. This means that strongly aberrated lenses must be located properly, without tilts or decentrations, or the aberrations will not completely cancel each other, as demonstrated by the through-focus MTF for a decentered second element shown in Figure 6C.

There are many four element lens types that are much better than the classical triplet and are usually employed to achieve higher performance than the triplet, but with some increase in cost. Even employing aspherical surfaces only results in limited improvement of a classical triplet because the stop is located too close to the negative element for the astigmatism to be corrected and the manufacturing sensitivity problem still remains.

SUMMARY OF THE INVENTION

In view of the foregoing, it is an object of the invention to provide improved objective lenses. More particularly, it is an object of the invention to provide objective lenses having improved aberration correction and reduced sensitivity to manufacturing variations. It is a further object of the invention to provide objective lenses which use a minimum of lens elements, e.g., three or four elements, where, preferably, all of the lens elements are composed of moldable materials and have aspherical surfaces.

To achieve the foregoing and other objects, the invention in accordance with certain of its aspects provides an optical system for producing an image of an object, said system having an overall positive optical power "Φ_0", an overall positive focal length "f_0" ($f_0 = 1/\Phi_0$), an object side, and an image side, and comprising in order from its object side to its image side of:

(a) a first lens unit (U1) having a negative power or a weak positive power (i.e., a positive power which is less than 0.3 times the overall positive power of the optical system and

preferably is less than 0.2 times the overall positive power) and an object side surface and an image side surface;

(b) a second lens unit (U2) having a positive power and an object side surface and an image side surface;

(c) a third lens unit (U3) having a negative power, the magnitude of the focal length of the third lens unit being less than 1.5 times the overall positive focal length of the optical system;

(d) an aperture stop (AS) between the object side surface of the first lens unit and the image side surface of the second lens unit; and

(e) at least one aspherical surface.

In certain preferred embodiments, the optical system has some or all of the following characteristics, either separately or in combination:

(1) each of the first, second, and third lens units comprises at least one aspherical surface;

(2) at least two of the first, second, and third lens units comprises two aspherical surfaces;

(3) each of the first, second, and third lens units comprises two aspherical surfaces;

(4) each of the first, second, and third lens units consists of a single lens element;

(5) the operative imaging components of the optical system, i.e., the components with optical power, consist of just the first, second, and third lens units;

(6) the operative imaging components of the optical system, i.e., the components with optical power, consist of just the first, second, and third lens units and each of those units consists of a single lens element;

(7) the optical system comprises a fourth lens unit (U4) on the image side of the third lens unit, said fourth lens unit having a positive power;

(8) the fourth lens unit comprises at least one aspherical surface;

(9) each of the first, second, third, and fourth lens units consists of a single lens element;

(10) the operative imaging components of the optical system, i.e., the components with optical power, consist of just the first, second, third, and fourth lens units;

(11) the operative imaging components of the optical system, i.e., the components with optical power, consist of just the first, second, third, and fourth lens units and each of those units consists of a single lens element;

(12) all lens elements used in the optical system are made from moldable materials, e.g., plastics or moldable glasses;

(13) the back focal length of the optical system is at least 0.5 times the overall positive focal length of the optical system;

(14) the exit pupil of the optical system is located at a distance from the image of at least 2 times the overall positive focal length of the optical system;

(15) the distance from the object side of the first lens unit to the image is less than 2 times the overall positive focal length of the optical system;

(16) at least one surface of the lens element nearest the image has an inflection;

(17) the optical system has a half field of view in the direction of the object of at least 25°;

(18) the optical system has a relative aperture of less than f/5, e.g., a relative aperture of f/4 or f/3.5;

(19) the optical system is used as a taking lens for a digital light sensor; and

(20) the optical system comprises sufficient aspherical surfaces to substantially correct third and fifth order aberrations and to substantially reduce the system's sensitivity to manufacturing deviations (tolerances).

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1A is a schematic side view of an inverse triplet lens constructed in accordance with the invention and having an f/# of 4.5, a semi-field of view of 25°, and a focal length (f') of 10 mm.

Figure 1B is a through-focus white light MTF at 50 cycles/mm for the inverse triplet of Figure 1A.

Figure 2A is a schematic side view of a desensitized inverse triplet constructed in accordance with the invention.

Figure 2B is a through-focus MTF at 50 cycles/mm for the inverse triplet of Figure 2A with the second element decentered by 0.025 mm.

Figure 3A is a schematic side view of an inverse triplet modified for an extended exit pupil position.

Figure 3B is a through focus MTF at 50 cycles/mm for the inverse triplet of Figure 3A.

Figure 4A is a schematic side view of an inverse triplet modified for an extended exit pupil position and a large back focal length.

Figure 4B is a through focus MTF at 50 cycles/mm for the inverse triplet of Figure 4A.

Figure 5A is a schematic side view of a further inverse triplet having an extended exit pupil position and a large back focal length.

Figure 5B is a through focus MTF at 50 cycles/mm for the inverse triplet of Figure 5A.

Figure 5C is a through focus MTF at 50 cycles/mm for the inverse triplet of Figure 5A with the first element (U1) decentered by 0.035 mm.

Figure 5D is a through focus MTF at 50 cycles/mm for the inverse triplet of Figure 5A with the second element (U2) tilted by 0.3°.

Figure 5E is a through focus MTF at 50 cycles/mm for the inverse triplet of Figure 5A with the third and fourth elements (U3 and U4) each tilted by 0.3°.

Figure 5F is a through focus MTF at 50 cycles/mm for the inverse triplet of Figure 5A with the air space between second and third elements (U2 and U3) changed by 0.04 mm.

Figure 5G is a through focus MTF at 50 cycles/mm for the inverse triplet of Figure 5A with the thickness of the second element (U2) changed by 0.04 mm.

Figure 6A is a schematic side view of a classical triplet having an f/# of 4, a semi-field of view of 25°, and a focal length (f') of 10 mm.

Figure 6B is a through-focus white light MTF plot at 50 cycles/mm for the classical triplet of Figure 6A at selected field positions.

Figure 6C is a through-focus white light MTF plot at 50 cycles/mm for the classical triplet of Figure 6A with second element decentered by 0.025 mm.

Prescriptions for the lenses of Figures 1-6 are set forth in Tables 1-6, respectively. The prescriptions of these tables use the "OSLO" format of the optical design program sold under that trademark by Sinclair Optics Inc., Rochester, New York.

The symbols used in the MTF plots have the following meanings: plus sign (+) -- on-axis; upward facing triangle (△) -- 0.7 field tangential; downward facing triangle (▽) -- 0.7 field sagittal; square (□) -- full field tangential; diamond (◇) -- full field sagittal; circle (○) -- ideal. The wavelengths used in calculating the MTF plots were 0.5461 microns, 0.4800 microns, and 0.6438 microns. The wavelengths were equally weighted.

The through-focus MTF plots of Figures 1B, 3B, 4B, and 6B are for full fields of ±25°, while those of Figures 2B, 5B-5G, and 6C are for a full field of ~±20°.

The foregoing drawings, which are incorporated in and constitute part of the specification, illustrate the preferred embodiments of the invention, and together with the description, serve to explain the principles of the invention. It is to be understood, of course, that both the drawings

and the description are explanatory only and are not restrictive or limiting of the invention.

DETAILED DESCRIPTION OF THE INVENTION

A. Dividing the Negative Power

As discussed above, the classical triplet with its positive, negative, positive configuration suffers from both aberration correction and manufacturability problems. In accordance with the invention, the powers of the classical triplet are inverted so that the lens has three lens units with a negative (or weak positive), positive, negative configuration. Figure 1A shows the basic structure of the inverse triplet lens of the invention.

By inverting the powers of the triplet, a different means of aberration correction is achieved. The stop is placed after the first element near the positive element, and the negative elements are allowed to be spaced somewhat from it.

In an all-spherical surface design, the single positive element contributes too much spherical aberration for the negative elements to correct, but the astigmatism can be well corrected with little secondary aberration residual. Unlike astigmatism, the spherical aberration can always be corrected with aspherics, and in fact the design form can be well corrected. The through-focus MTF of Figure 1B shows the improved astigmatism correction as compared to the classical triplet (see Figure 6B).

B. Manufacturing Desensitization

While the inverse triplet requires aspherical surfaces for full correction, only one or two aspheres are required, depending on the field and aperture desired. For molded lenses, only the cost of tooling is increased if additional aspherics are added, and this cost is easily justified if the manufacturing yield is increased. By allowing all of the surfaces to become aspherical, the design can be tailored for particular manufacturing processing.

Figure 2A shows a design modified to minimize effects of tilting, decentering, and spacing errors. A comparison of through-focus MTF for

about 0.75 relative field is shown in Figure 2B where the second lens element is decentered.

Table 7 compares the sums of the primary and secondary aberrations for each element of the classical triplet of Figure 6A and the desensitized inverse triplet of Figure 2A. As can be seen in this table, the approximate aberration correction of the individual inverse triplet lens elements is better than those of the classical triplet.

For manufacturing purposes, the most important characteristic is whether any of the tolerances required is too severe for mass production, even if all of the other tolerances are very loose. The next level is the cost associated with too many restrictive tolerances. The use of multiple aspherical surfaces provides the means to accomplish both of these goals. That is, if a sufficient number of surfaces are aspherical, there are more degrees of freedom than required for aberration correction, so the lens can be optimized for manufacturability.

C. Modification for Extended Exit Pupil Position

For imaging with a single polychromatic sensor it is often necessary to limit the angle of maximum chief rays so as to avoid color artifacts caused by the separation of the color filter and the actual active sensor. Satisfying this telecentric, or nearly telecentric condition, requires additional positive power in the space between the objective lens and the image. Ideally, a lens at the image could perform the function of extending the exit pupil without introducing severe aberrations. In actual practice this space is usually occupied with filters of various types so the positive lens is removed somewhat.

By adding positive power, field curvature is increased as well, and because there is no significant choice of plastic materials, correction requires either larger size or additional negative power. The aspherical surfaces are sufficient to correct for the aberrations resulting from this increased power, and even the ability to desensitize remains.

It seems possible to place the positive lens anywhere in the image space. If it is placed near the image, shown in Figure 3A, only spherical surfaces are required. If aspherical surfaces are used the departure from sphericity of the additional lens becomes very noticeable. This design, shown in Figure 4A, looks like a conventional triplet with negative element added to the front. The aberration correction, however, is quite different because the stop is located a substantial distance from the central negative element.

It is interesting to note how the aspherical surfaces can be used to correct the aberrations in different ways. The sum of the Seidel and fifth order surface contributions lens element by lens element is shown in Tables 8 and 9 for the designs shown in Figure 3A and 4A, respectively. By adding the additional aspheres the lens of Figure 4A has less spherical aberration per lens element, and thus is less sensitive to manufacturing errors of decentration. Because the positioning and tilting of the sensor itself can usually be adjusted to remove the effects of a tilted image, the larger lens element contribution for off-axis aberrations can be tolerated.

The through-focus MTF at 50 cycles/mm for the extended exit pupil designs of Figures 3A and 4A are shown in Figures 3B and 4B, respectively. The designs show some astigmatism for the corner of the image (25 degrees semi-field), but compare quite favorably with the conventional triplet without the extended pupil.

Figure 5A illustrates a further lens design which (1) has an extended pupil, (2) has a long back focal length, and (3) employs sufficient aspherical surfaces so as to reduce substantially the design's sensitivity to manufacturing deviations (tolerances). In particular, a comparison of Figure 5B with Figures 5C-5G demonstrates the relative insensitivity of this design to decentration (Figure 5C), tilt (Figures 5D and 5E), spacing errors (Figure 5F), and element thickness errors (Figure 5G).

Although preferred and other embodiments of the invention have been described herein, further embodiments may be perceived by those

skilled in the art without departing from the scope of the invention as defined by the following claims.

TABLE 1

SRF	RADIUS	THICKNESS	APERTURE RADIUS	GLASS	SPE	NOTE
OBJ	--	5.8238e+19	2.7157e+19	AIR		
1	-3.064874 V	2.400264 V	1.779136 S	ACRYL C	*	
2	-7.562037 V	0.248357 V	1.488879 S	AIR		
AST	3.722346 V	2.313840 V	1.419980 AS	ACRYL C	*	
4	-3.051072 V	0.500484 V	1.830093 S	AIR		
5	-2.329861 V	1.033262 V	1.814661 S	STYRE C	*	
6	-7.191681 V	5.000000	2.095155 S	AIR	*	
7	--	0.874400	3.393300 S	BK7 C		
8	--	4.315274 S	3.542750 S	AIR		
IMS	--	-0.091852 V	4.639273 S			

*CONIC AND POLYNOMIAL ASPHERIC DATA

SRF	CC	AD	AE	AF	AG
1	--	0.016073	-0.001518	0.000291	-2.1617e-05
3	--	-0.014628	-0.001961	1.8097e-05	-5.8687e-05
5	--	0.046559	-0.000971	-4.3232e-05	8.7316e-05
6	--	0.028145	-0.000172	-0.000283	4.1117e-05

*WAVELENGTHS: 0.540000 0.450000 0.620000

*REFRACTIVE INDICES

GLASS	RN1	RN2	RN3	VNBR
ACRYL	1.492403	1.499298	1.488808	46.940121
STYRE	1.595772	1.611790	1.587636	24.665717
BK7	1.519039	1.525320	1.515539	53.071437

Working F-number:	4.499908
Field angle:	25.000000
Effective focal length:	10.000093

UNIT	POWER	EFL
1	-0.078720	-12.703311
2	0.260570	3.837735
3	-0.159153	-6.283258

TABLE 2

SRF	RADIUS	THICKNESS	APERTURE RADIUS	GLASS	SPE	NOTE
OBJ	--	1.0000e+20	3.6397e+19	AIR		
1	-1.871869 V	0.882563 V	1.400000 K	ACRYL	C	*
2	-2.078649 V	0.077102	1.468745 S	AIR		*
AST	--	1.362577 V	1.443414 AS	AIR		
4	4.385774 V	2.038735 V	1.700000 K	ACRYL	C	*
5	-4.896073 V	0.218500	1.982925 S	AIR		*
6	-2.583927 V	1.752980 V	1.959875 S	CARBO	C	*
7	-7.200777 V	5.000000	2.300000 K	AIR		*
8	--	0.873000	3.089841 S	BK7	C	
9	--	3.121103 S	3.176392 S	AIR		
IMS	--	--	3.646332 S			

*CONIC AND POLYNOMIAL ASPHERIC DATA

SRF	CC	AD	AE	AF	AG
1	--	0.022092	0.004971	-0.002012	0.000759
2	--	0.016915	0.001905	-0.000566	0.000228
4	--	-0.000542	-0.001445	-1.7676e-05	-2.1005e-05
5	--	0.000532	-0.000913	9.7818e-05	-2.6015e-05
6	--	0.029750	-0.001536	0.000357	-1.7813e-05
7	--	0.015015	-0.000516	0.000157	-1.7916e-05

*WAVELENGTHS: 0.546100 0.480000 0.643800

*REFRACTIVE INDICES

GLASS	RN1	RN2	RN3	VNBR
ACRYL	1.492067	1.496540	1.487978	57.474701
CARBO	1.590088	1.600365	1.580754	30.090095
BK7	1.518721	1.522829	1.514721	63.978408

Working F-number: 4.007073
Field angle: 20.000000
Effective focal length: 10.018215

UNIT	POWER	EFL
1	0.010658	93.823764
2	0.197291	5.068654
3	-0.125789	-7.949799

TABLE 3

SRF	RADIUS	THICKNESS	APERTURE RADIUS	GLASS	SPE	NOTE
OBJ	--	5.8238e+19	2.7157e+19	AIR		
1	-2.668669 V	2.400985 V	1.886256 S	ACRYL	C	*
2	-5.645963 V	0.432900 V	1.695983 S	AIR		
AST	3.787009 V	3.639209 V	1.580753 AS	ACRYL	C	*
4	-3.143441 V	0.721000 V	2.143264 S	AIR		
5	-2.452537 V	1.551295 V	2.067523 S	STYRE	C	*
6	-42.455643 V	5.000000	2.000000 K	AIR		*
7	15.018072 V	2.000000	4.267459 S	BK7	C	
8	-12.712902 V	3.861206 S	4.550894 S	AIR		
IMS	--	-0.038531 V	4.663557 S			

*CONIC AND POLYNOMIAL ASPHERIC DATA

SRF	CC	AD	AE	AF	AG
1	--	0.019180	-0.001186	0.000194	2.4289e-06
3	--	-0.011463	-0.000298	-5.0005e-05	-3.0879e-05
5	--	0.027499	-0.001863	0.000268	2.1667e-05
6	--	0.016636	-0.001448	0.000153	-1.0934e-05

*WAVELENGTHS: 0.540000 0.450000 0.620000

*REFRACTIVE INDICES

SRF	GLASS	RN1	RN2	RN3	VNBR
1	ACRYL	1.492403	1.499298	1.488808	46.940121
3	ACRYL	1.492403	1.499298	1.488808	46.940121
5	STYRE	1.595772	1.611790	1.587636	24.665717
7	BK7	1.519039	1.525320	1.515539	53.071437

Working F-number:	4.201221
Field angle:	25.000000
Effective focal length:	10.003465

UNIT	POWER	EFL
1	-0.071410	-14.003548
2	0.237003	4.219364
3	-0.225574	-4.433135
4	0.073531	13.599728

TABLE 4

SRF	RADIUS	THICKNESS	APERTURE RADIUS	GLASS	SPE	NOTE
OBJ	--	1.0000e+20	4.6631e+19	AIR		
1	-1.981542 V	0.956852 V	1.400000 K	ACRYL	C	*
2	-2.437039 V	0.094142	1.420000	AIR		*
AST	--	2.527223 V	1.430000 AK	AIR		
4	4.551250 V	3.503587 V	3.170000	ACRYL	C	*
5	-5.535989 V	0.667224	3.170000	AIR		*
6	-2.557747 V	0.517987 V	2.880000	CARBO	C	*
7	-7.7229e+03 V	1.338772	2.600000 K	AIR		*
8	35.060881 V	2.904450 V	4.000000	ACRYL	C	*
9	-4.739874 V	3.277058	4.000000	AIR		*
10	--	1.000000	5.000000	BK7	C	
11	--	3.287032 S	5.000000	AIR		
IMS	--	-0.036095 V	4.662896 S			

*CONIC AND POLYNOMIAL ASPHERIC DATA

SRF	CC	AD	AE	AF	AG
1	--	0.025922	0.002042	-0.000232	0.000238
2	--	0.015826	-0.000156	0.000365	-5.1713e-05
4	--	0.001478	-0.000500	5.3849e-05	-1.3072e-06
5	--	0.003161	0.001368	-0.000325	2.6057e-05
6	-1.000000	0.032196	-0.004592	0.000323	-7.2973e-06
7	--	0.026643	-0.003928	0.000316	-1.1361e-05
8	--	-5.3670e-05	0.000288	-2.8108e-05	4.8652e-07
9	--	0.002044	-0.000103	1.4479e-05	-6.6382e-07

*WAVELENGTHS: 1 0.546100 0.480000 0.643800

*REFRACTIVE INDICES

GLASS	RN1	RN2	RN3	VNBR
CARBO	1.590088	1.600365	1.580754	30.090095
ACRYL	1.492067	1.496540	1.487978	57.474701
BK7	1.518721	1.522829	1.514721	63.978408

Working F-number: 3.999787
Field angle: 25.000000
Effective focal length: 10.000000

UNIT	POWER	EFL
1	-0.014259	-70.129963
2	0.174436	5.732754
3	-0.230624	-4.336065
4	0.115013	8.694691

TABLE 5

SRF	RADIUS	THICKNESS	APERTURE RADIUS	GLASS	SPE	NOTE
OBJ	--	1.8280e+03	908.000000	AIR		
1	-2.702181 V	0.993383 V	2.250000	ACRYL	C *	
2	-3.057447 V	3.503000	2.300000	AIR	*	
AST	--	1.526000	1.230000 AK	AIR		
4	5.478221 V	2.593481 V	1.900000	ACRYL	C *	
5	-5.441035 V	1.255000	1.960000	AIR	*	
6	-2.181334 V	1.000000	1.960000	CARBO	C *	
7	21.138383	0.800000	2.700000	AIR	*	
8	7.220047 V	2.505124	3.400000	ACRYL	C *	
9	-3.781015 V	1.280000	3.500000	AIR	*	
10	--	0.500000	5.000000	GLASS16	M	
11	--	--	5.000000	AIR		
12	--	1.400000	5.000000	GLASS18	M	
13	--	--	5.000000	AIR		
14	--	1.000000	5.000000	BK7	C	
15	--	3.096984 S	5.000000	AIR		
IMS	--	-0.020000	5.000000			

*CONIC AND POLYNOMIAL ASPHERIC DATA

SRF	CC	AD	AE	AF	AG
1	--	0.010789	0.000437	3.4575e-05	8.5312e-06
2	--	0.008419	8.2533e-05	8.7405e-05	-6.4345e-06
4	--	0.002926	0.000486	5.2554e-06	1.9254e-06
5	-0.500000	0.003504	7.6571e-05	0.000364	-4.5360e-05
6	--	0.004121	0.002268	0.000353	2.1025e-05
7	--	-0.009885	0.000660	7.1870e-05	-1.1261e-05
8	--	-0.003873	-7.1717e-05	4.5720e-05	-2.1033e-06
9	--	0.004438	0.000142	-1.1630e-05	2.0009e-06

*WAVELENGTHS: 0.546100 0.480000 0.643800

*REFRACTIVE INDICES

GLASS	RN1	RN2	RN3	VNBR
CARBO	1.590088	1.600365	1.580754	30.090095
ACRYL	1.492067	1.496540	1.487978	57.474701
GLASS16	1.518721	1.522835	1.514727	63.978408
GLASS18	1.550000	1.555122	1.545122	55.000000

TABLE 5 (continued)

Working F-number:	4.010265
Field angle:	26.372434
Effective focal length:	8.708503

UNIT	POWER	EFL
1	-0.001647	-607.021954
2	0.166139	6.019058
3	-0.303181	-3.298355
4	0.183403	5.452484

TABLE 6 – PRIOR ART

SRF	RADIUS	THICKNESS	APERTURE RADIUS	GLASS	SPE	NOTE
OBJ	--	1.0000e+19	4.6631e+18	AIR		
1	3.618229 V	1.516310 V	2.021492 K	GLASS1 M		
2	6.708656 V	0.357025	1.458777	AIR		
3	-5.035902 V	0.186013	1.445575	GLASS3 M		
4	4.352446 V	0.241346 V	1.283532	AIR		
5	8.221513 V	0.602167 V	1.271637	GLASS5 M		
6	-4.236010 V	0.081008 V	1.126154	AIR		
AST	--	8.299840 S	1.010817 AK	AIR		
IMS	--	-0.073304 V	4.631058 S			

*WAVELENGTHS: 0.587560 0.480000 0.643800

*REFRACTIVE INDICES

GLASS	RN1	RN2	RN3	VNBR
GLASS1	1.744000	1.754114	1.740592	55.022000
GLASS3	1.784700	1.803037	1.778831	32.418000
GLASS5	1.834000	1.847665	1.829490	45.885000

Working F-number:	4.000002
Field angle:	25.000000
Effective focal length:	10.000005

UNIT	POWER	EFL
1	0.114551	8.729745
2	-0.339039	-2.949517
3	0.291767	3.427392

TABLE 7

Classical	SA	CMA	AST	Inverse	SA	CMA	AST
Element 1	-.053	-.017	-.088	Element 1	-.020	.099	.083
Element 2	.203	-.034	.522	Element 2	-.092	.097	-.134
Element 3	-.150	.054	-.429	Element 3	.089	-.171	-.005

TABLE 8

Lens Element	SA	CMA	AST	DIST
1	-.376	.140	.012	-.373
2	-.041	-.099	-.103	-.069
3	.425	-.025	.002	.461
4	-.003	-.006	.036	-.235

TABLE 9

Lens Element	SA	CMA	AST	DIST
1	-.126	.013	.096	-.245
2	-.062	.269	.234	.209
3	.089	-.153	.229	-1.67
4	-.025	-.034	-.660	.503

What is claimed is:

1. An optical system for producing an image of an object, said system having an object side, an image side, an overall positive focal length f_0, and comprising in order from its object side to its image side of:

(a) a first lens unit having:

(i) a negative power or a weak positive power; and

(ii) an object side surface and an image side surface;

(b) a second lens unit having:

(i) a positive power; and

(ii) an object side surface and an image side surface;

and

(c) a third lens unit having a negative power, the magnitude of the focal length of the third lens unit being less than 1.5 times f_0;

wherein said optical system has:

(i) at least one aspherical surface; and

(ii) an aperture stop between the object side surface of the first lens unit and the image side surface of the second lens unit.

2. The optical system of Claim 1 wherein each of the first, second, and third lens units comprises at least one aspherical surface.

3. The optical system of Claim 1 wherein at least two of the first, second, and third lens units comprises two aspherical surfaces.

4. The optical system of Claim 1 wherein each of the first, second, and third lens units comprises two aspherical surfaces.

5. The optical system of Claim 1 wherein each of the first, second, and third lens units consists of a single lens element.

6. The optical system of Claim 1 wherein the components of the optical system with optical power consist of just the first, second, and third lens units.

7. The optical system of Claim 6 wherein the first, second, and third lens units each consists of a single lens element.

8. The optical system of Claim 1 further comprising a fourth lens unit on the image side of the third lens unit, said fourth lens unit having a positive power.

9. The optical system of Claim 8 wherein the fourth lens unit comprises at least one aspherical surface.

10. The optical system of Claim 8 wherein each of the first, second, third, and fourth lens units consists of a single lens element.

11. The optical system of Claim 8 wherein the components of the optical system with optical power consist of just the first, second, third, and fourth lens units.

12. The optical system of Claim 11 wherein the first, second, third, and fourth lens units each consists of a single lens element.

13. The optical system of Claim 1 wherein all lens elements used in the optical system are made from moldable materials.

14. The optical system of Claim 8 wherein all lens elements used in the optical system are made from moldable materials.

15. The optical system of Claim 1 wherein the back focal length of the optical system is at least 0.5 times f_0.

16. The optical system of Claim 8 wherein the back focal length of the optical system is at least 0.5 times f_0.

17. The optical system of Claim 8 wherein the exit pupil of the optical system is located at a distance from the image of at least 2 times f_0.

18. The optical system of Claim 1 wherein the distance from the object side of the first lens unit to the image is less than 2 times f_0.

19. The optical system of Claim 8 wherein the distance from the object side of the first lens unit to the image is less than 2 times f_0.

20. The optical system of Claim 1 wherein at least one surface of the lens element nearest the image has an inflection.

21. The optical system of Claim 8 wherein at least one surface of the lens element nearest the image has an inflection.

22. The optical system of Claim 1 wherein the system has a half field of view in the direction of the object of at least 25°.

23. The optical system of Claim 8 wherein the system has a half field of view in the direction of the object of at least 25°.

24. The optical system of Claim 1 wherein the system has a relative aperture of less than f/5.

25. The optical system of Claim 8 wherein the system has a relative aperture of less than f/5.

26. The optical system of Claim 1 wherein the system comprises sufficient aspherical surfaces to substantially correct third and fifth order aberrations and to substantially reduce the system's sensitivity to manufacturing deviations.

27. The optical system of Claim 8 wherein the system comprises sufficient aspherical surfaces to substantially correct third and fifth order aberrations and to substantially reduce the system's sensitivity to manufacturing deviations.

28. A digital camera comprising the optical system of Claim 1 and a digital light sensor.

29. A digital camera comprising the optical system of Claim 8 and a digital light sensor.

30. An optical system comprising first and second lens elements, the first lens element having first and second aspherical surfaces and the second lens element having third and fourth aspherical surfaces, wherein the first and second aspherical surfaces at least partially correct at least one primary aberration of the first lens element and the third and fourth aspherical surfaces at least partially correct at least one primary aberration of the second lens element, said corrections being sufficient to reduce the sensitivity of the optical system to at least one manufacturing tolerance.

31. The optical system of Claim 30 wherein the first and second aspherical surfaces at least partially correct the spherical aberration of the

first lens element and the third and fourth aspherical surfaces at least partially correct the spherical aberration of the second lens element.

32. The optical system of Claim 30 wherein the first lens element has a positive power and the second lens element has a negative power.

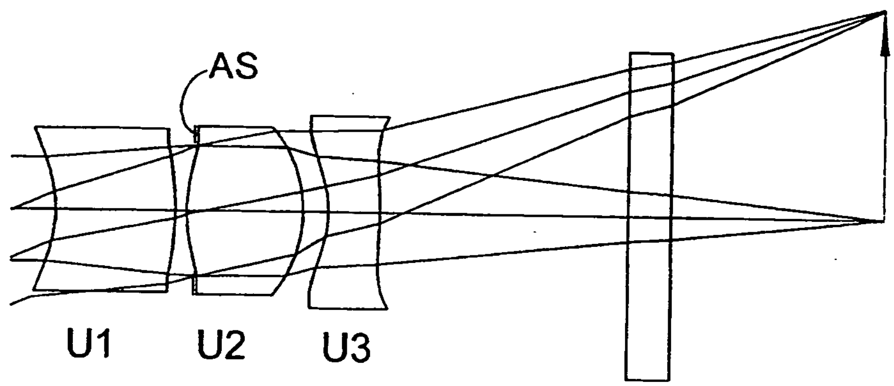
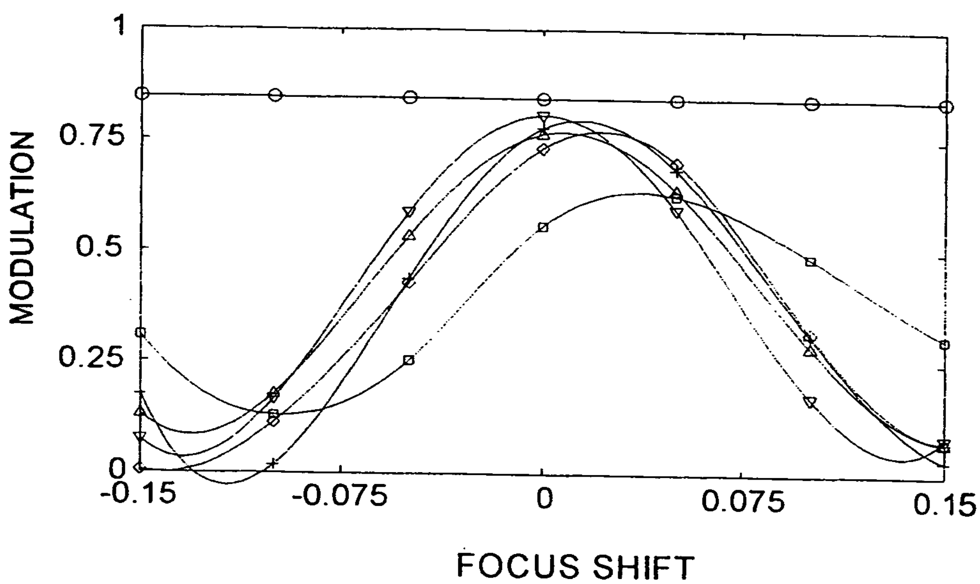

AS
U1
U2
U3

FIG. 1A


MODULATION
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0.15
FOCUS SHIFT

FIG. 1B

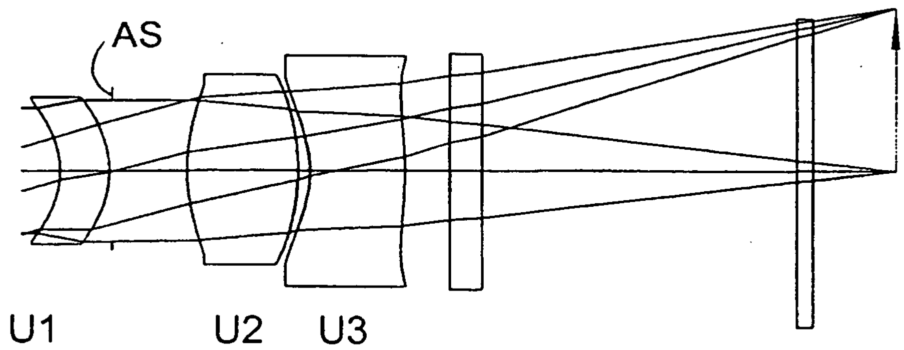
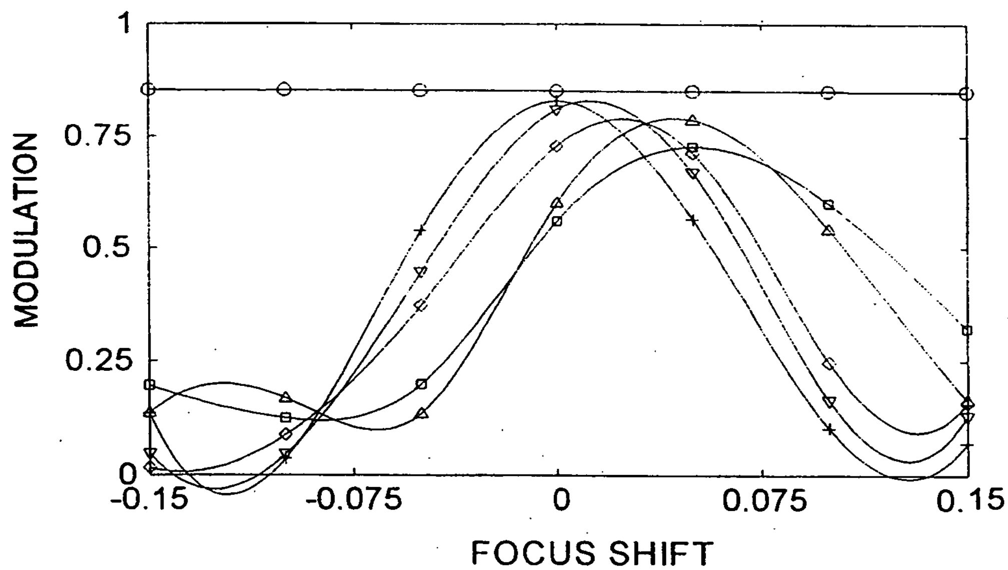

AS
U1
U2
U3

FIG. 2A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0.25
0
MODULATION
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-0.075
0
0.075
0.15
FOCUS SHIFT

FIG. 2B

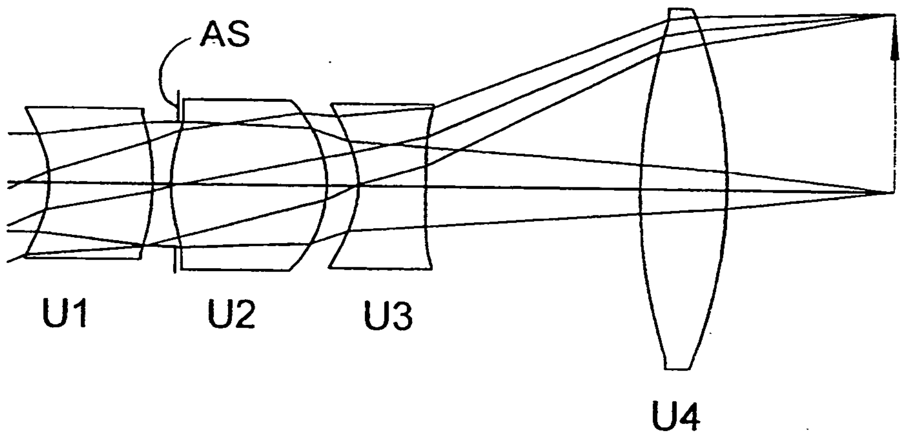
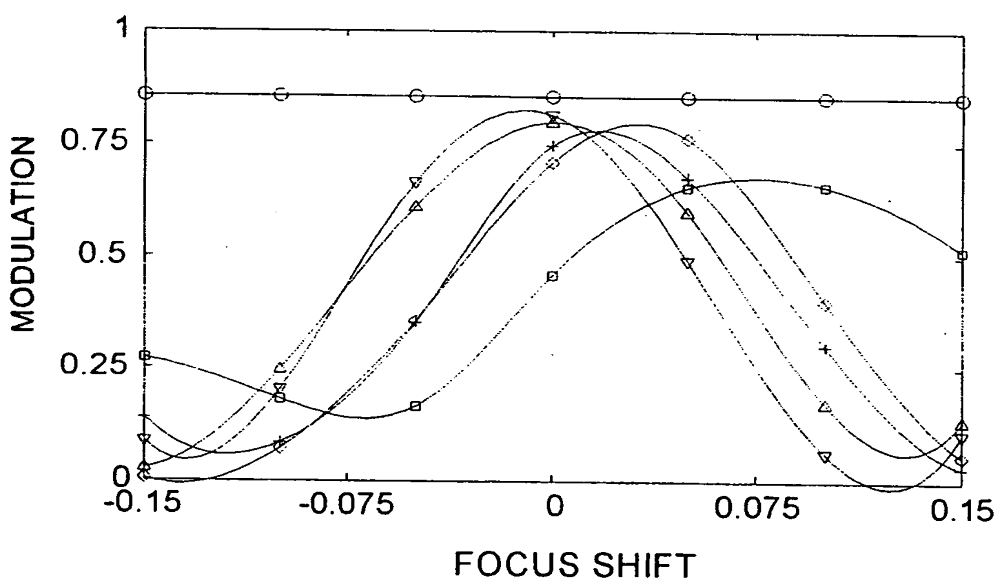

AS
U1
U2
U3
U4

FIG. 3A


MODULATION
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0
-0.15
-0.075
0
0.075
0.15
FOCUS SHIFT

FIG. 3B

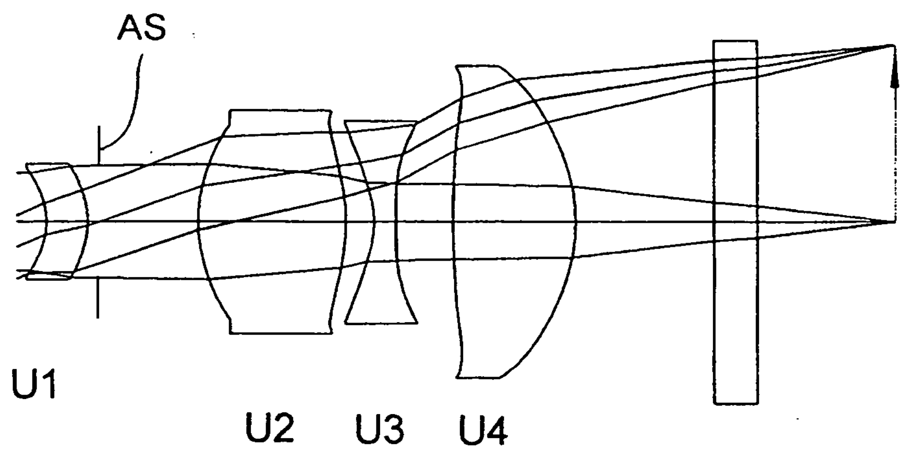

AS
U1
U2
U3
U4

FIG. 4A

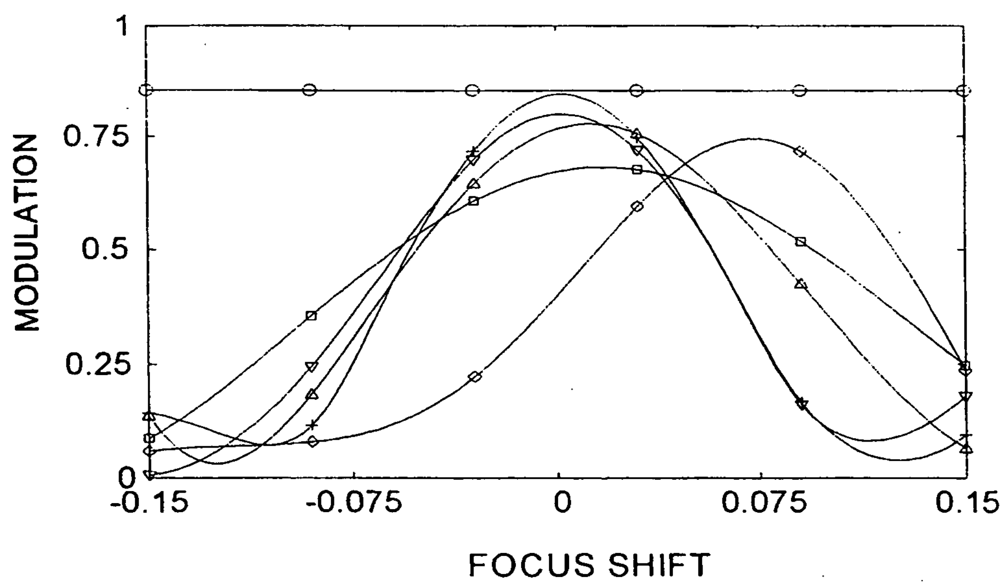

1
0.75
0.5
0.25
0
MODULATION
-0.15
-0.075
0
0.075
0.15
FOCUS SHIFT

FIG. 4B

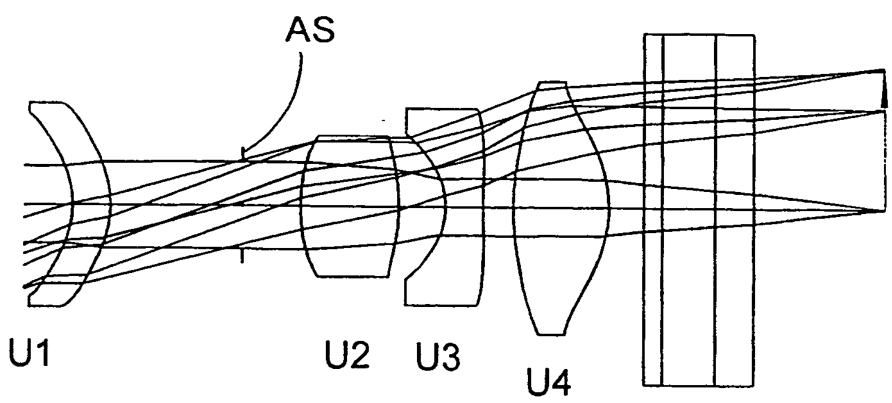
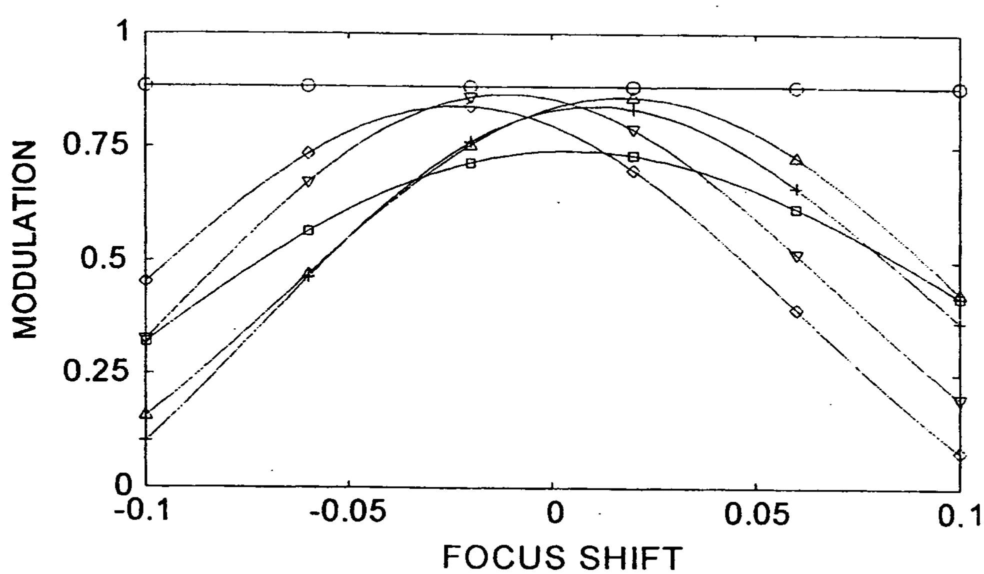

AS
U1
U2
U3
U4

FIG. 5A


1
0.75
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MODULATION
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0
0.05
0.1
FOCUS SHIFT

FIG. 5B

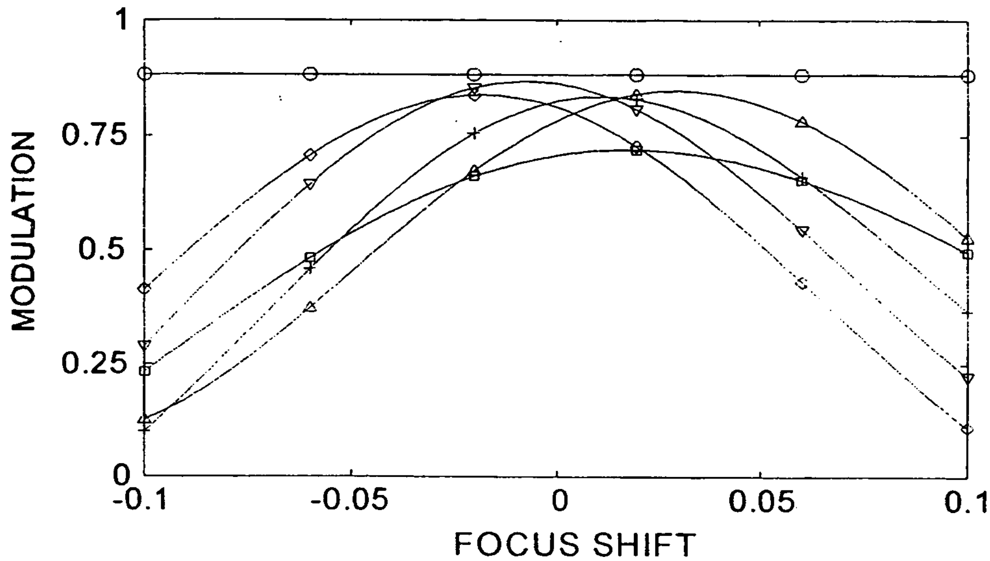
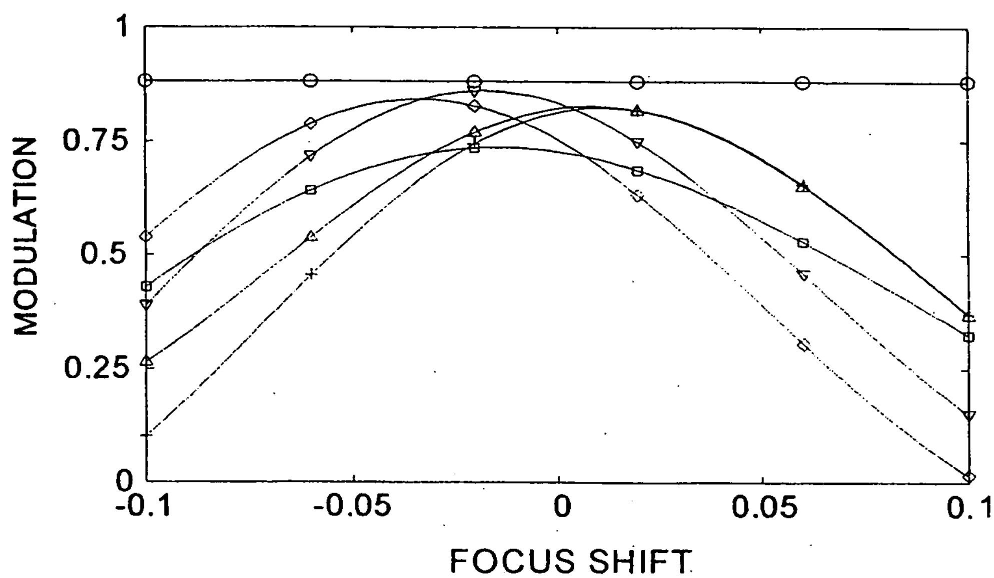

1
0.75
0.5
0.25
0
MODULATION
-0.1
-0.05
0
0.05
0.1
FOCUS SHIFT

FIG. 5C


1
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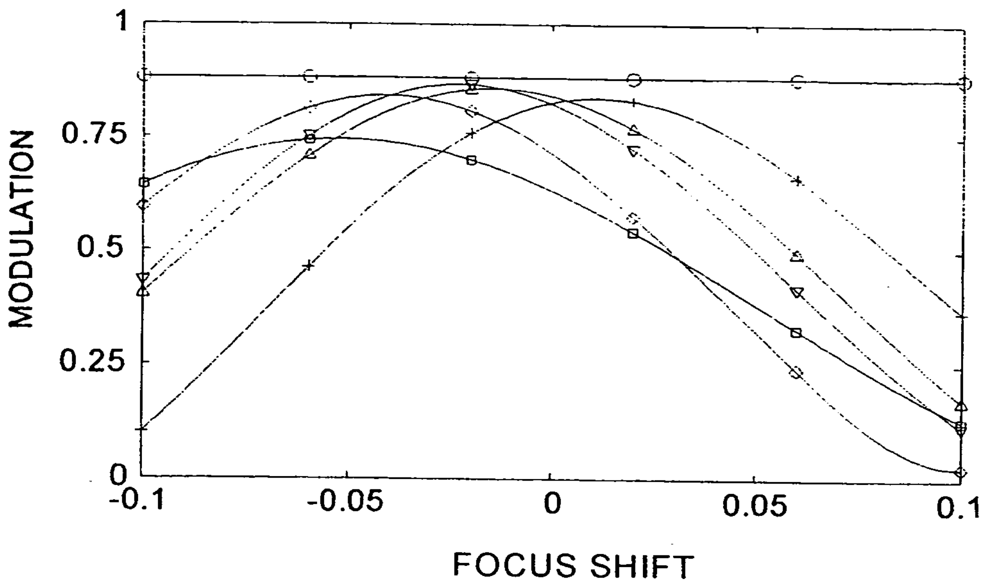
0
MODULATION
-0.1
-0.05
0
0.05
0.1
FOCUS SHIFT

FIG. 5D


1
0.75
0.5
0.25
0
MODULATION
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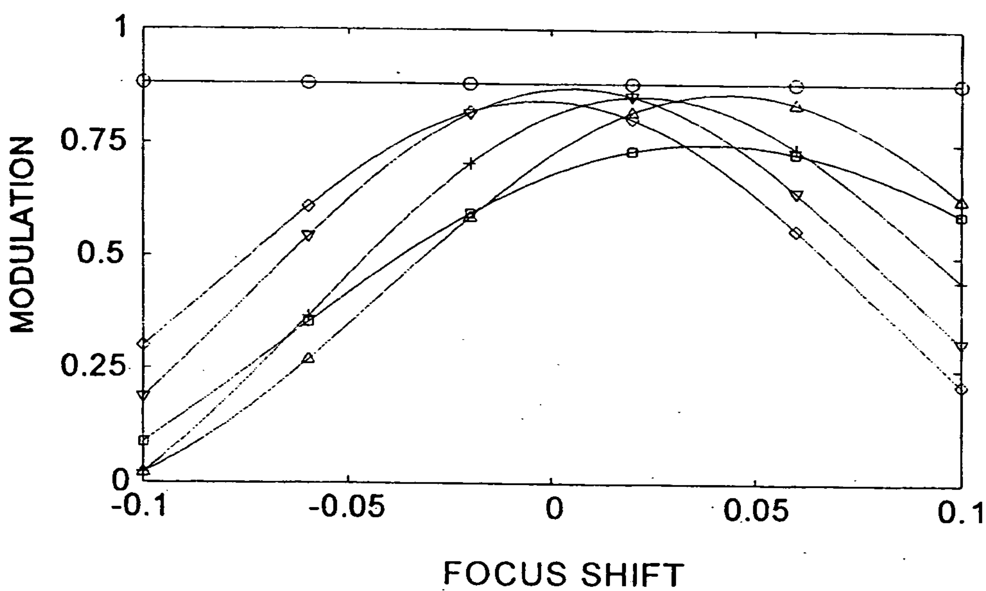
-0.05
0
0.05
0.1
FOCUS SHIFT

FIG. 5E


1
0.75
0.5
0.25
0
MODULATION
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-0.05
0
0.05
0.1
FOCUS SHIFT

FIG. 5F

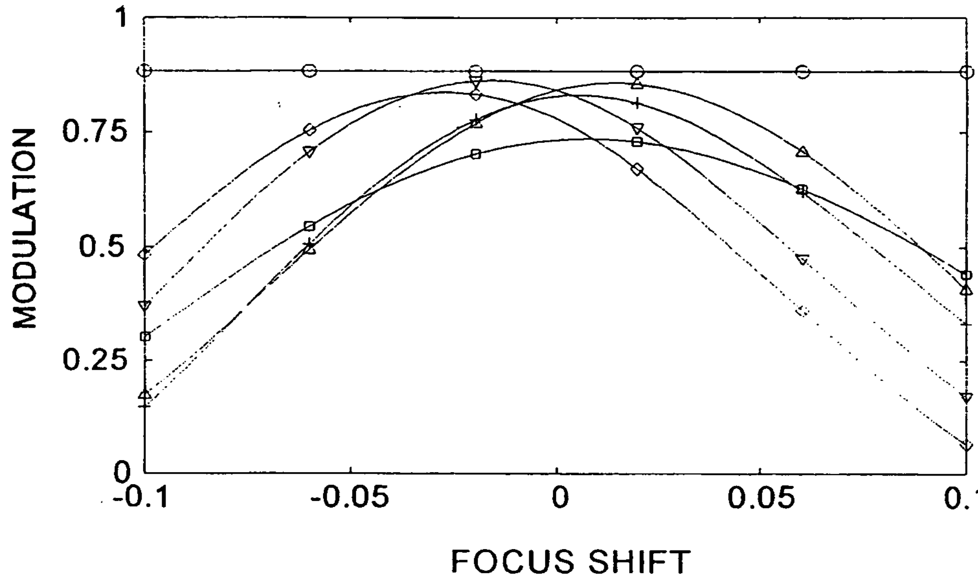

FIG. 5G

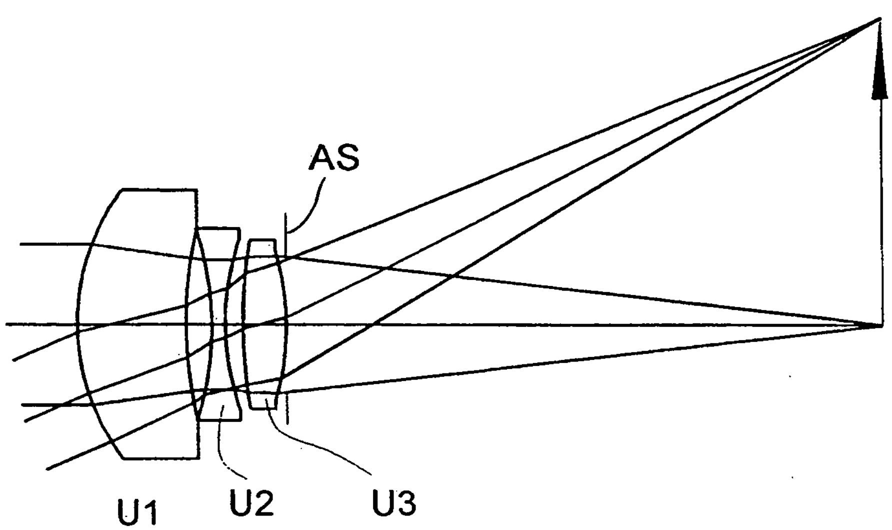

FIG. 6A - PRIOR ART

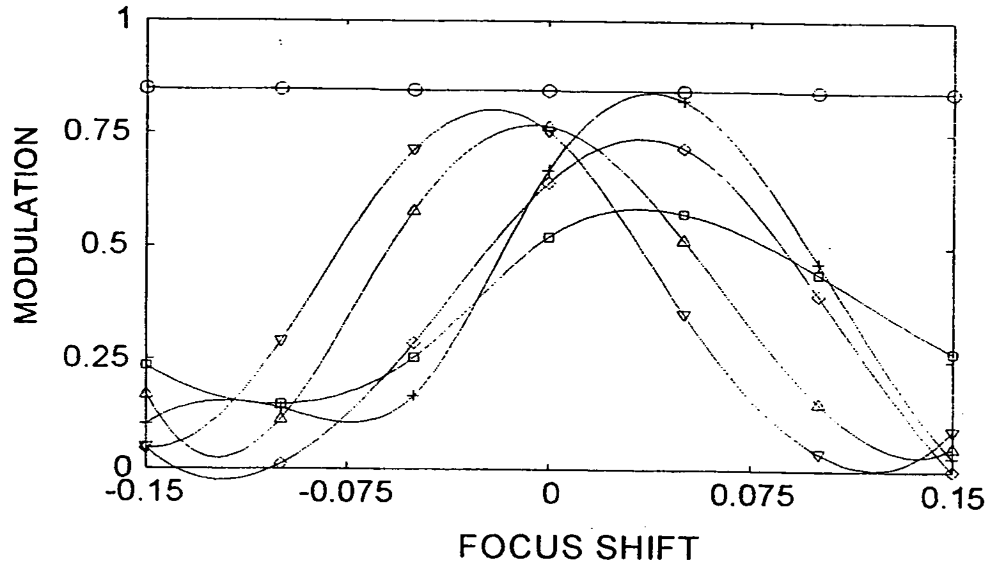

FIG. 6B - PRIOR ART

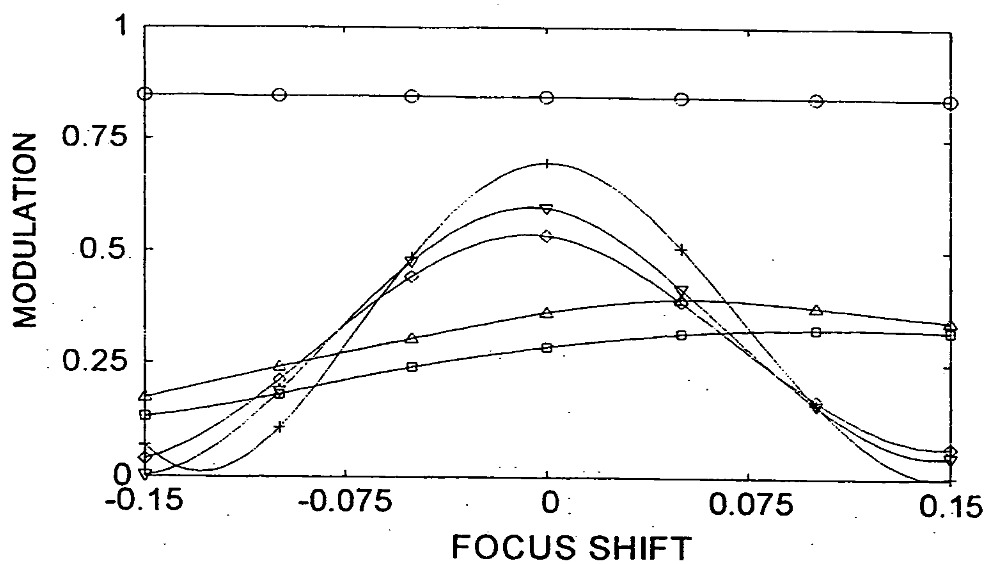

FIG. 6C - PRIOR ART

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US99/12658

A. CLASSIFICATION OF SUBJECT MATTER

IPC(6) : G02B 13/04, 9/34, 3/02
US CL : 359/753, 784, 716
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

U.S. : 359/715, 716, 753, 781, 784

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 5,251,073 A [SCHAUSS] 5 October 1993, see entire document, especially, column 1, line 53-column 3, line 12.	1, 3, 4, 8, 13, 20-23, 26-29
Y	US 4,109,995 A [BETENSKY] 29 August 1978, see entire document, especially column 1, line 6-column 8, line 24	1,3, 5-7
Y	US 4,781,449 A (HIRAKAWA et al.] 01 November 1999, see entire document, especially column 1, line 5-column 8, line 55.	1, 3, 5-7
A	US 5,617,255 A [YAMADA] 01 April 1997, see entire document.	1-32
A	US 5,204,781 [ISHIBAI et al.] 20 April 1993, see entire document.	5-7, 10-21

☐ Further documents are listed in the continuation of Box C. ☐ See patent family annex.

* Special categories of cited documents:

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier document published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
09 AUGUST 1999	23 SEP 1999
Name and mailing address of the ISA/US Commissioner of Patents and Trademarks Box PCT Washington, D.C. 20231 Facsimile No. (703) 305-3230	Authorized officer GEORGIA Y. EPPS Telephone No. (703) 308-4883